Next Generation High Efficiency Boosted Engine Development

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Ford Motor Company

Project ID #: ACE156
DE-EE0008878

June 4th, 2020
1:30 pm
30-Minute

Project Overview

Partners

FEV North America Inc.
Oak Ridge National Lab (ORNL)

Barriers

- Engine efficiency can be improved by increasing the compression ratio (CR). CR is limited by autoignition (knock), heat losses, and unfavorable combustion chamber shapes.
- Dilute stoichiometric combustion offers benefits in engine efficiency but is limited by combustion stability and exhaust gas recirculation (EGR) flow capacity.
- Engine friction, pumping work, and accessory loads must be minimized to improve net efficiency.
- Reducing vehicle mass improves fuel economy but is limited by structural requirements and manufacturing techniques.

Timeline

Project start:	4Q 2019
Project end:	4Q 2022
Percent complete:	15%

Budget

Total project funding: $10M

- DOE share: $7,566,731
  - EERE: $7,416,731
  - FFRDC: $150,000
- Recipient: $2,433,269

- Budget period 1: $3,419,937
- Budget period 2: $5,135,831
- Budget period 3: $1,444,232

Any proposed future work is subject to change based on funding levels

Project Relevance

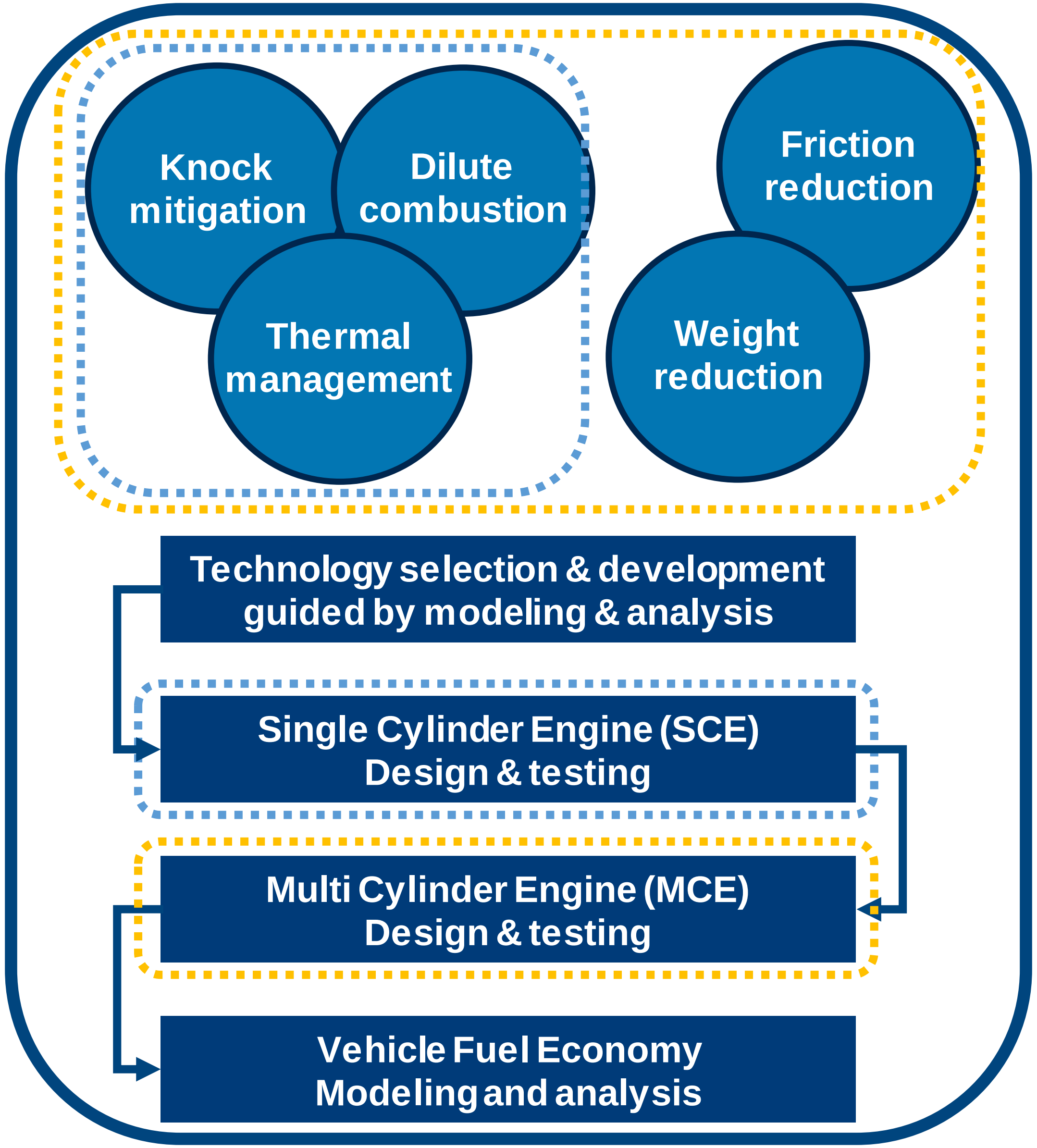
Objective: Design, evaluate, build and test an engine that will achieve 23% fuel economy improvement and 15% weight reduction relative to a 2016MY 3.5L V6 EcoBoost F150 baseline.

Impact: Technologies investigated in this project will reduce CO_2 emissions of the highest production volume powertrains found in light duty vehicles by addressing the following barriers:

- Knock mitigation
- Dilute combustion
- Friction reduction
- Thermal management
- Weight reduction

Project supports the VTO Advanced Combustion Engine and Fuels Subprogram goals of improving light-duty engine efficiency, reducing mass and hence improving passenger vehicle fuel economy.

Project Approach



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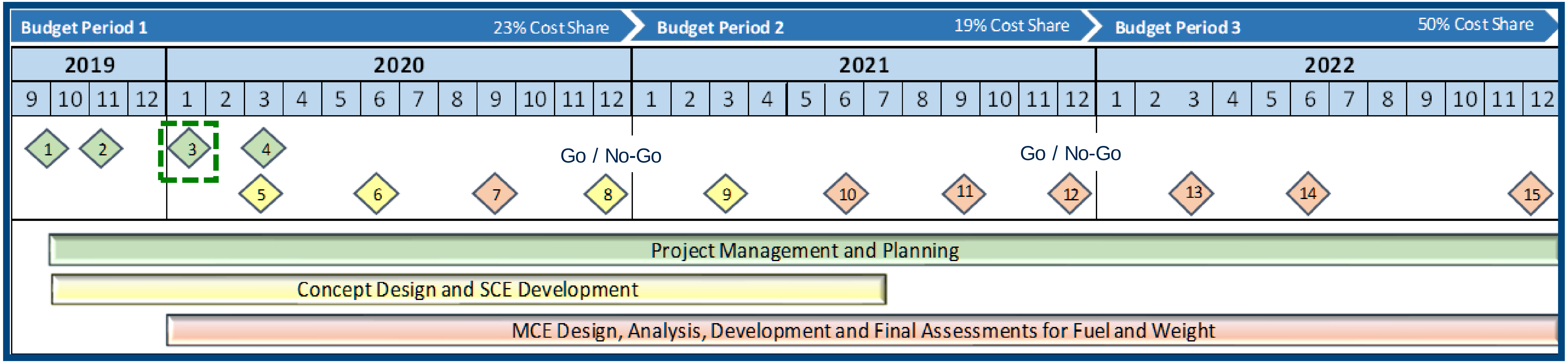
Project Milestones



#	Date	Event/ Milestone	%
1	10/01/19	Conditional award effective	100
2	11/13/19	DOE on-site kick-off	100
3	01/27/20	Definitized DOE award executed	100
4	03/16/20	FEV sub-contract executed, PO issued	100
5	03/31/20	SCE assumptions, targets & hard points defined	100
6	06/30/20	SCE hardware frozen, 3-plug and pre-chamber	75
7	09/30/20	Composite oil pan concept selected	10
8	12/31/20	Analytical assessment of combustion metrics	5

#	Date	Event/ Milestone	%
9	03/31/21	SCE development complete & MCE ignition selected	5
10	06/30/21	MCE design frozen	5
11	09/30/21	MCE hardware procurement	5
12	12/31/21	Analytical assessment of SCE & MCE design vs. targets	5
13	03/31/22	MCE built, install and debug complete	0
14	06/30/22	Initial fuel consumption map complete	0
15	12/31/22	Final assessment of vehicle fuel economy & engine weight	0

Delays due to COVID 19 are expected but can not be quantified at this time.

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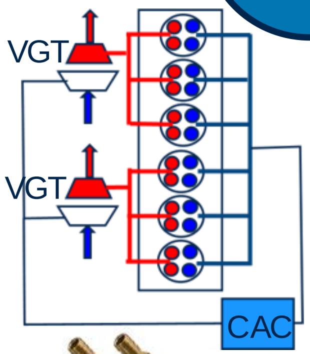
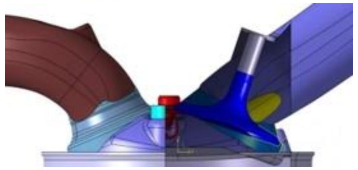
Technical Accomplishments and Progress

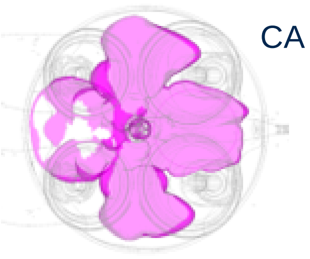
Knock Mitigation

1D & 3D modeling used to investigate technologies enabling increased Compression Ratio (CR).

- **Baseline CR: 10:1, targeting 13-15:1 enabled by:**
  - **Miller cycle operation at high load**
    - » **Advanced boost system**
    - » **Continuously variable valvetrain**
    - » **Effective intercooling (exploring additive manufacturing)**
  - **Thermal management of combustion chamber surfaces**
    - » **Intake port cooling / insulation, thermal barrier coated port side of intake valves, hollow / sodium cooled valves, high thermal conductivity valve guides, valve seats and rings, advanced split cooling, advanced piston cooling**
  - **Fast burn rate**
    - » **Advanced ignition systems**
    - » **Long stroke -> favorable surface to volume ratio, short flame travel distance, high piston speed for generating charge motion**
  - **Cooled EGR**







CA 726

1D simulation results show that peak power performance targets are achievable at 14:1 CR.
Further improvements for low speed torque are being investigated.

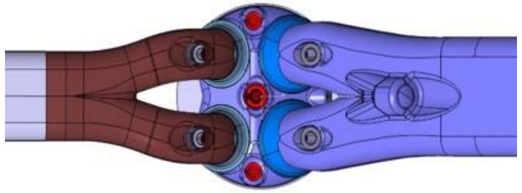
Technical Accomplishments and Progress

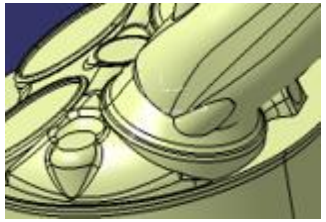
Dilute combustion | Knock Mitigation

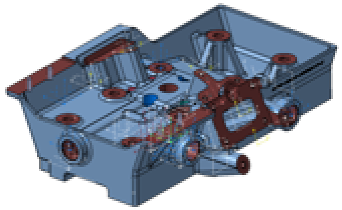
Two Versions of Single Cylinder Combustion System Hardware Designed and Analyzed

Three traditional spark plug concept

- Conservative approach using known technology
- Allows largest valve sizes to maximize flow
- Single cylinder hardware manufacture almost complete

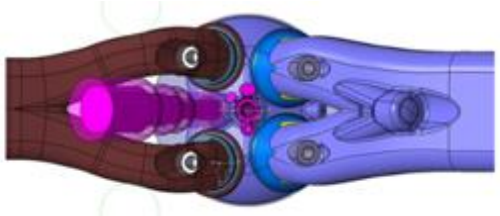


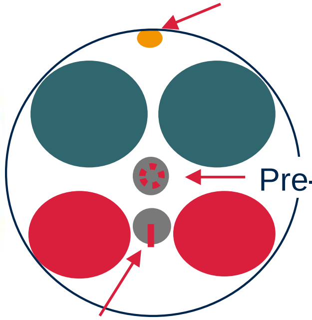


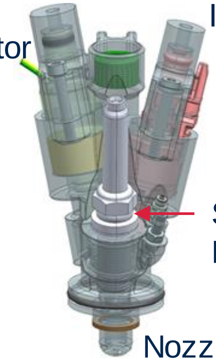


Active Pre-chamber concept

- Promises faster burn rate than 3-plug
- Cartridge system allows separate or premixed fuel + air
- Includes a main-chamber spark plug for cold start







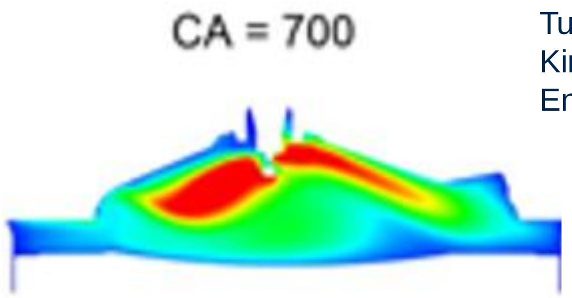
- Improved package efficiency and synergistic integration with valvetrain, fuel and cooling subsystems
- Port fuel injection (PFI) and side direct injection (DI) on both concepts, plus third fuel injector for prechamber concept

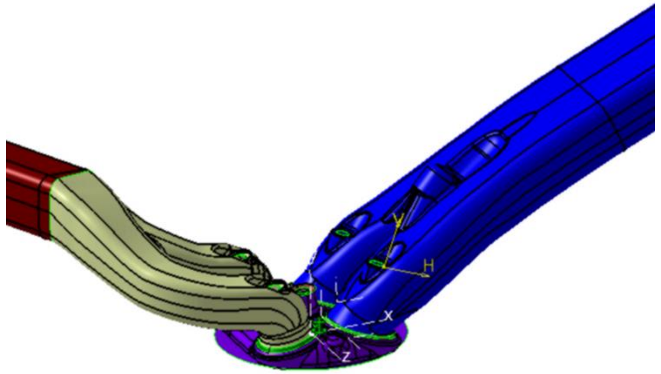
Two combustion system design concepts developed for single cylinder engine testing.

Technical Accomplishments and Progress

Dilute combustion

- **0.75 Bore/Stroke ratio selected for favorable combustion chamber shape at high compression ratio.**
- **Long stroke provides high piston speed and strong charge motion for improved burn rate and mixing.**
- **Combustion system port design parameterized and optimized for flow, mixing and burn rate improvement using 3D computational fluid dynamics (CFD)**





3D modeling has been extensively used to design the intake ports and combustion chamber surface geometry for dilute stoichiometric combustion

Technical Accomplishments and Progress

Thermal Management

Heat Loss Reduction Strategy and Evaluation

Reduced Surface-to-Volume Ratio

- Reducing bore-to-stoke ratio results in less fuel energy lost as heat to chamber walls and the cooling system
- Fuel consumption and design sensitivity studies were conducted to evaluate benefits and trade-offs of long stroke designs
- A target bore-to-stroke ratio of 0.75 was established for the project

Low Heat Capacity Coatings

- Coating combines low conductivity and low heat capacity so surface 'follows' gas temperature
- Multiple coatings evaluated analytically for brake thermal efficiency (BTE), knock tendency, engine durability and application production feasibility
- Compared to traditional engine deposits at an equivalent thickness, coatings provided up to 2% BTE improvement and better knock performance
- A coating was selected and applied to prototype parts for evaluation

Coated piston & valves

Reducing heat losses to the combustion chamber / cooling system is critical to fuel economy and guided component design requirements for the project.

Technical Accomplishments and Progress

Friction Reduction

There are many areas being optimized for reduced friction, including:

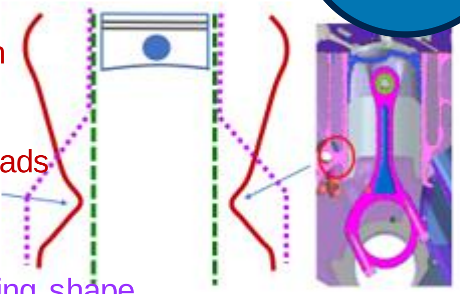
Cylinder Bore-

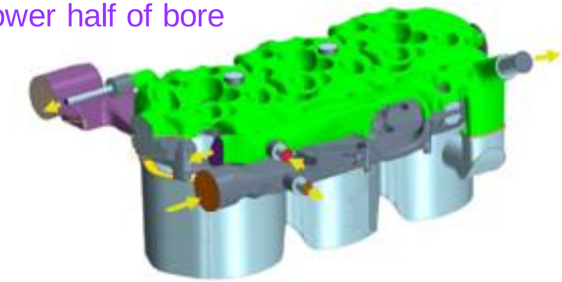
- **Cylinder bore shaping via articulated honing tools (mechanically honing an inverse shape) and improved cooling (reducing non-uniform thermal expansion) via split cooling are being developed to improve the hot, running cylinder bore shape to reduce piston skirt friction and enable a reduction in ring tensions without negatively impacting oil consumption.**

- **Several iterations of block geometry and cooling strategies have been analyzed on the I6 block, as well as surrogate work (I3 cooling jackets shown) to improve the bore geometry.**

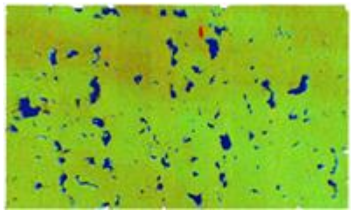
- **High porosity (good oil retention for lubrication) thermally sprayed cylinder liners combined with a mirror finish is in development to improve ring and skirt sliding friction.**

- **Surrogate testing has been ongoing using different coatings to assess friction opportunities as well as ring surface finish (nitriding, physical vapor deposition (PVD), diamond-like coating (DLC)).**





Split cooling concept



3D profile of High Porosity Bore Coating

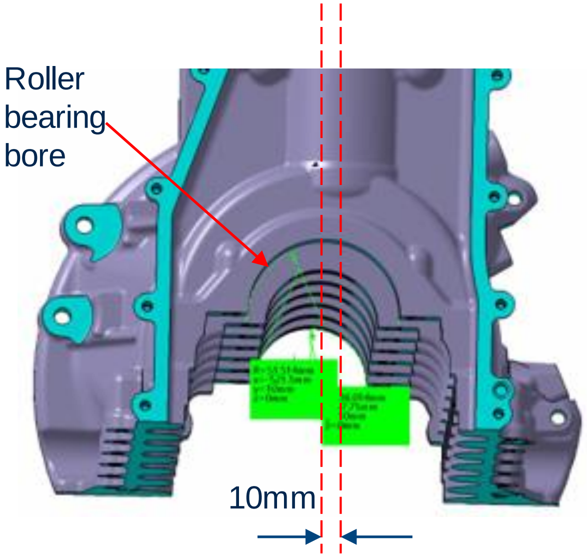
Reducing skirt friction and lowering ring tensions are major focus of friction reduction

Technical Accomplishments and Progress

Friction Reduction

Additional developments in reduced friction include:

- 10 mm crank offset to reduce piston side forces on the cylinder liner
- Implementing a roller bearing on the #1 crank main to replace a traditional journal bearing (see larger bore required in block) for lower friction
- Using non-contacting (low friction) crank seals, front and rear.
- Lubrication team is testing lower viscosity oils to better understand
  - Wear rates and durability concerns (rings, oil pump, etc.)
  - Measuring friction reduction under various operating conditions
  - Effects on subsystem function (i.e. oil pump sizing and main oil gallery pressure)
- A fully variable mechanical oil pump as well as an optional supplemental electric oil pump are being investigated to reduce pump size requirements and parasitic losses



Multiple actions across subsystems being investigated & implemented to reduce total engine friction

Any proposed future work is subject to change based on funding levels

Technical Accomplishments and Progress

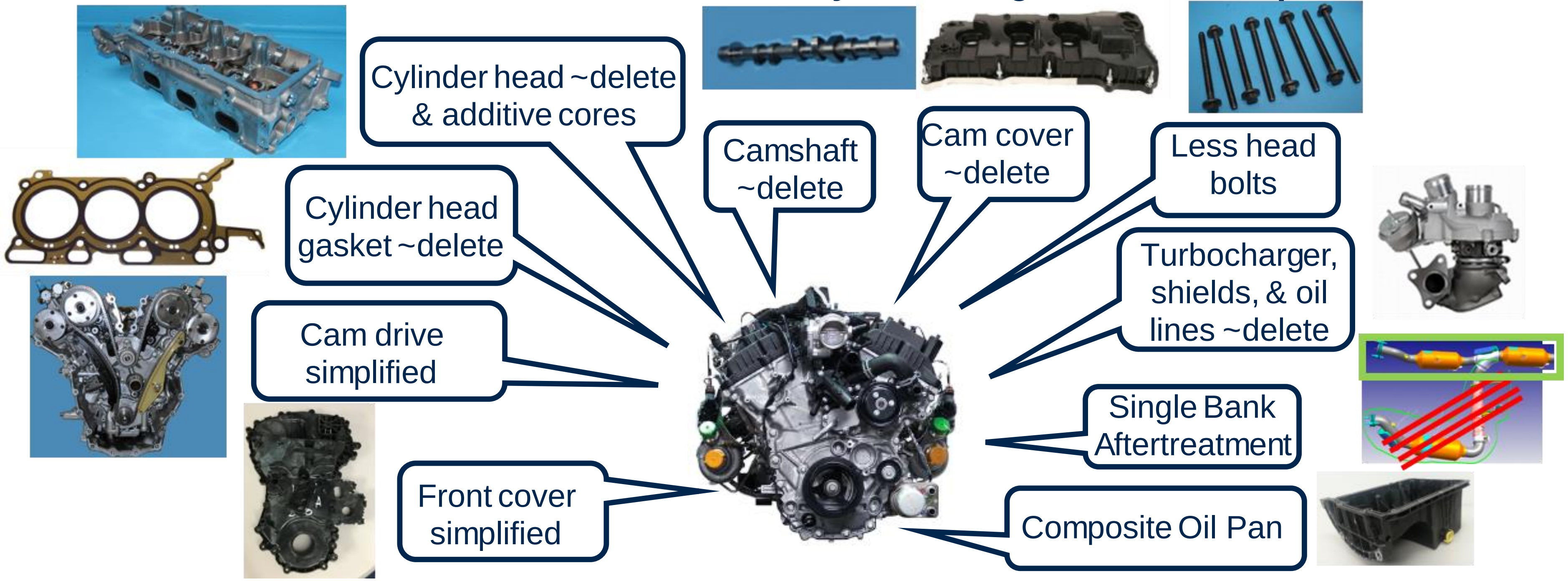
Weight Reduction

Planned Weight Actions

Architecture change, advanced materials, integrated exhaust manifold, additive cores, continuously variable valve lift (CVVL), plasma transfer wire arc (PTWA) bores instead of cast iron liners

Weight Risks

Additional hardware such as sensors, advanced boost system, longer stroke, and pre-chamber hardware



Weight reduction will be a challenge for the project. Considerable attention needs to be given to weight during the component design and development process to understand the trade-offs.

Response to Previous Year Reviewers' Comments

- **Not applicable. This is the 1st AMR presentation for this project.**

Collaboration and Coordination with Other Institutions

Industry Subrecipient Project Partner

- Co-design / co-development of pre-chamber
- Intake air system design / development
- EGR system design / development
- Piston design / development
- Lubrication system design / development
- CAD support for various components

DOE VTO National Laboratory Partner

- Co-design / development of composite structural oil pan
- Material selection, tool development, part production

Any proposed future work is subject to change based on funding levels

Remaining Challenges and Barriers

- The technologies added to achieve the engine efficiency goals have increased the challenge of meeting the weight reduction target.
- Limited active pre-chamber experimental data is available for correlating 3D combustion models.
- Peak power results look promising at the target compression ratio, but 1D modeling predicts a shortfall in full load torque at low engine speed.
- Meeting the crank stiffness requirements to avoid torsional vibration challenges have resulted in larger main bearings increasing friction and mass.

Proposed Future Research

- **Budget Period 1 – Concept Design and Analysis** **Oct. 2019 – Dec. 2020**
  - Single Cylinder Engine (SCE) Development
    - » Build two SCEs with different combustion chamber configurations; a multi-plug design and a pre-chamber design
    - » Use dynamometer testing to demonstrate the capabilities of each concept to meet intermediate combustion metrics (dilution tolerance, burn rate etc.) to support fuel economy and emission objectives.
  - Multi-Cylinder Engine (MCE) Design
    - » Select leading SCE concept to move forward into the MCE design effort
    - » Initiate cylinder head, cylinder block and other long lead/interfacing components

- **Budget Period 2 – Component Development & SCE Testing** **Jan. 2021 – Dec. 2021**
  - Continue SCE dynamometer testing to support MCE-specific design concerns
  - Deliver MCE cylinder head hardware by mid-Q3 2021
  - Deliver remaining MCE hardware by late Q4 2021

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Summary

- This project has recently started but significant design and analysis work has been completed.
- The first single cylinder engine is under construction and the second single cylinder engine design work is nearly complete.
- Designs are not yet mature enough to assess against the 23% fuel economy and 15% weight targets. Status updates will be available in subsequent AMR presentations.
- Delays due to COVID 19 are expected but can not be quantified at this time.

Technical Backup Slides

Objectives

Design, evaluate, build and test an engine achieving 23% fuel economy improvement and 15% weight reduction relative to a 2016MY 3.5L V6 EcoBoost F150.

Vehicle	2016MY F150
Engine Displacement	3.5L 6 Cylinder GTDI 4V
Transmission	6R80 Auto
Weight	5250 lbs ETW
Fuel Economy	4WD: 17MPG (15 City / 20 Hwy)
Emissions Level	Tier 2 Bin 4
Fuel Type	Regular Gasoline
Engine As Shipped Weight	184 kg
Peak Thermal Efficiency	36.7%
Peak Power	365HP @ 5000rpm
Peak Torque	420lb-ft @ 2500rpm
Passenger and Cargo	7599 GVWR
Towing Capabilities	12,200 lbs

Any proposed future work is subject to change based on funding levels

Estimated Fuel Economy Benefits

Proposed Actions	Baseline	% FE Improvement	Comments
13:1–15:1 CR	10:1	6-8	Requires significant knock mitigation. Airpath thermal mgt., split and optimized cooling system, miller valve events, lube system optimization for piston cooling, high conductivity valve seats and guides
35-50% Cooled EGR	0%	2-5	Requires advanced ignition (active pre-chamber, multi-plug or other unconventional ignition technologies) and boost system improvements
B/S opt: 0.72-0.82	1.06	1.0-2.0	Efficiency / CR enabler, likely requires architecture changes
CVVL	Ti-VCT	2.5-3.5	Enables Miller and transient fuel economy
Stop-Start	-	3.0-4.0	
Down speeding	6 speed	2.0-4.0	10 speed transmission in place of 8 speed
Temperature swing coatings	-	1-2	Reduced heat losses with less intake charge heating
Friction reduction	base	1-2	Form hone, high porosity PTWA with mirror finish, roller bearings, variable displacement oil pump, offset crank, advanced cooling strategy, split and optimized flow paths.
Fast warm-up	base	0.2	Advanced cooling system
Weight reduction		1	Weight reduction achieved through architecture change, composite materials, and additive manufacturing largely offset by adding EGR system and upgrading the boost system.
Engine upsizing	base	-1.7	Increased displacement to offset lower power density
Total		~23	

Any proposed future work is subject to change based on funding levels

Estimated Engine Weight Walk

Proposed Actions	% Weight Reduction	Comments
Engine architecture	5.2	Shift from a “V” to an “I” architecture
Advanced materials	2.7	Carbon fiber compression-molded oil pan, composite carbon fiber compression-molded front cover (not included), additive hollow titanium connecting rods (not included), composite engine mounts (not included), composite rear seal carrier (not included)
Exhaust manifolds	3.6	Eliminate two cast steel manifolds and integrate into the cylinder head
Single bank aftertreatment	3.5	Reduced number of catalysts bricks, cans and sensors.
Optimized cylinder head	1.2	Use indirect additive manufacturing to optimize head for weight
CVVL	1.3	Delete (2) intake cams and valvetrain hardware
Optimized cylinder block	0.8	Use indirect additive manufacturing to optimize block for weight. (not included in prototype)
PTWA	1.2	Replace (6) cast iron bore liners with plasma transfer wire arc (PTWA) coating
Battery optimization	3.4	Replace 12V flooded / wet cell lead acid with Li-ion 12V starter battery
EGR system	-3.3	Baseline does not have an EGR system so there is a weight increase for hardware (valve, cooler, tubes, sensors, and wiring)
Engine thermal actions	-1.8	Additional piston cooling jets, valves and sensors to manage the advanced cooling system, liquid cooled CAC – dry weight
Long stroke	-2.7	Deck height increase up to 20mm
Net Weight Savings	**15.1**	

Weight reduction actions total 22.9%

Weight additions total 7.8%

Any proposed future work is subject to change based on funding levels